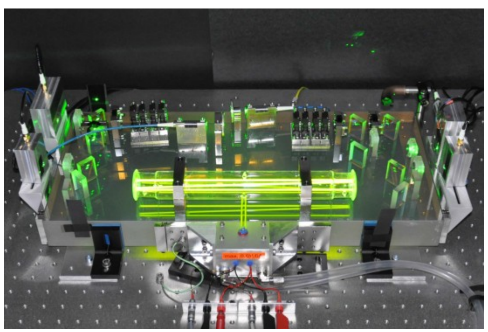
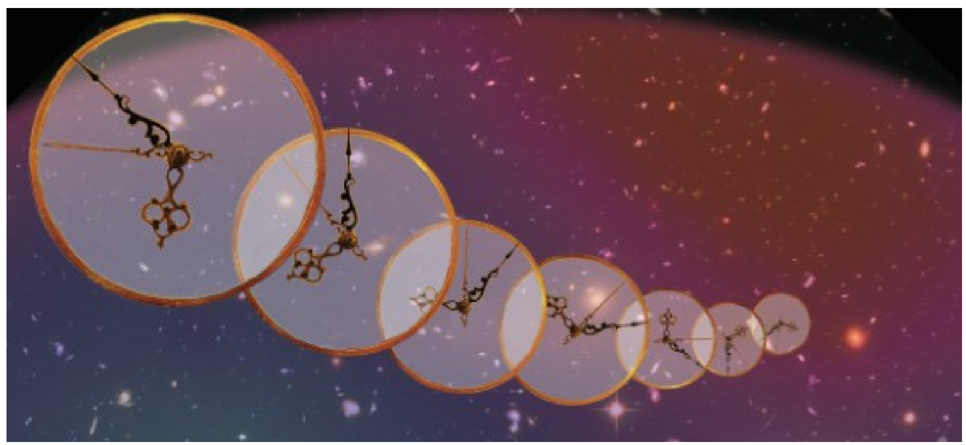
mSTAR: Space-Time Asymmetry Research

Testing Lorentz Invariance in Low-Earth Orbit





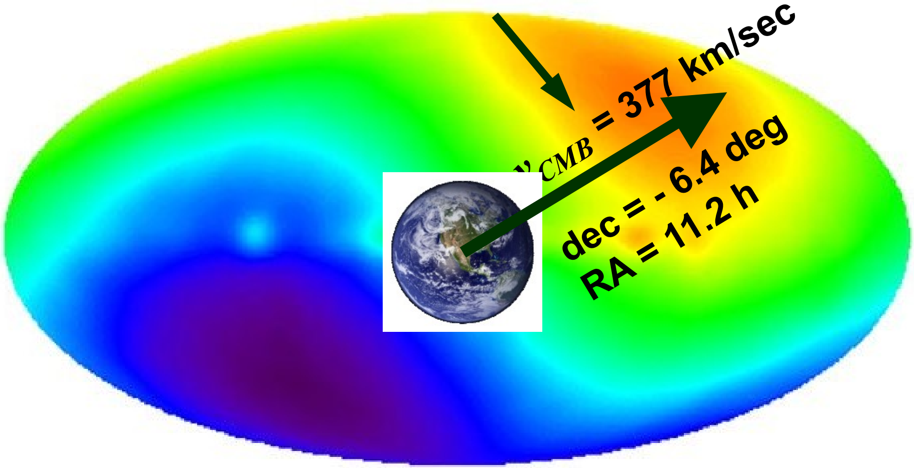
Sasha Buchman for the mSTAR team

October 17th , 2013

Kinematic Approach to LIV

RMS approach:
- -Robertson (1949)
- -Mansouri &
- -Sexl (1977)

Is the CMB a preferred frame?



$$\frac{\Delta}{c} = C_{MM} \sin^2 \theta_{INSTR} \left(\frac{v_{INSTR} - v_{CMB}}{c} \right)^2 + C_{KT} \left(\frac{v_{INSTR} - v_{CMB}}{c} \right)^2$$

Michelson Morley Coefficient (C_{MM})

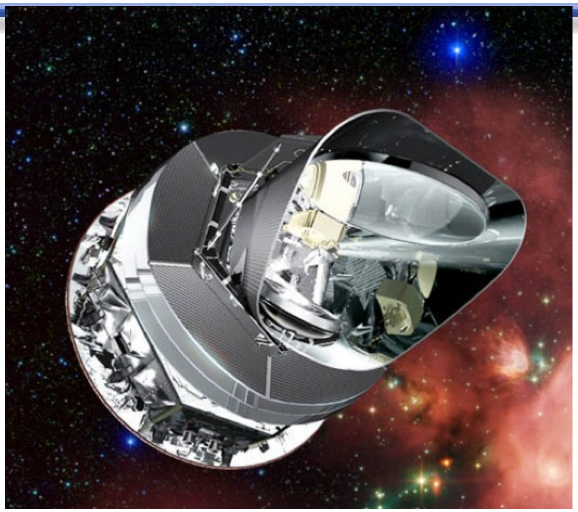
Kennedy Thorndike Coefficient (C_{KT})

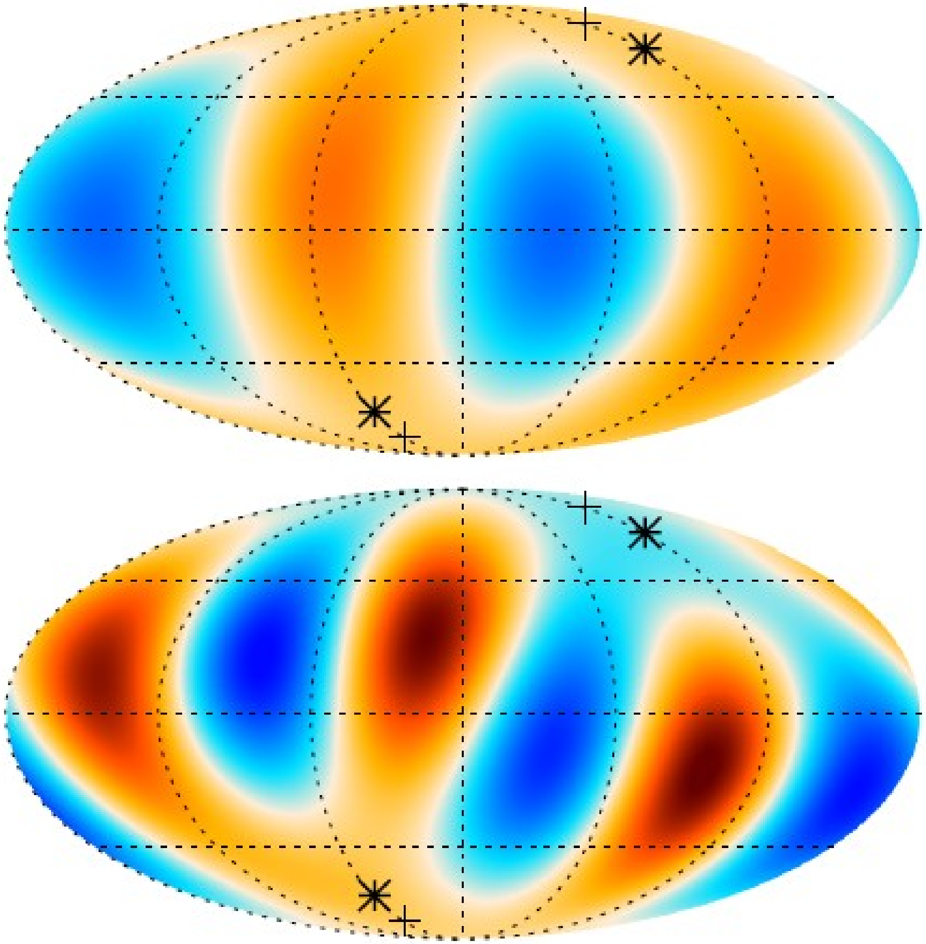
v_{INSTR}, v_{CMB} = velocities of instrument, preferred frame (PF)

θ_{INSTR} = angle of light beam (instrument) to the PF

in Special Relativity $C_{MM} = C_{KT} = 0$

Planck CMB data analysis (2013)





Upper: the derived quadrupole (temperature range ±35 micro-K).
Lower: the derived octopole (temperature range ±35 micro-K).
Cross and star signs indicate axes of the quadrupole and octopole, respectively, around which the angular momentum dispersion is maximized.

-Planck collaboration, arXiv, 1303.5083v1

Why Measure *c* Invariance?

Colladay and Kostelecky (1997)

"The natural scale for a fundamental theory including gravity is governed by the Planck mass M_P, which is about 17 orders of magnitude greater than the electroweak scale m_W associated with the standard model. This suggests that observable experimental signals from a fundamental theory might be expected to be suppressed by some power of the ratio:

$$r \approx \frac{m_W}{M_P} \sim 10^{-7}$$

THE mSTAR SENSITIVITY COULD CLOSE THAT GAP

Why KT in Space?

- **Kennedy-Thorndike signal enhancement**
  - Signal modulated at satellite orbital variation **~1.5 hr**
  - Signal modulated at orbital velocity differences **±7 km/s**
    - Diurnal Earth rotation signal **<0.30 km/s @ 24 hr**
    - Yearly Earth orbital motion signal at **30 km/s @ 8766 hr**

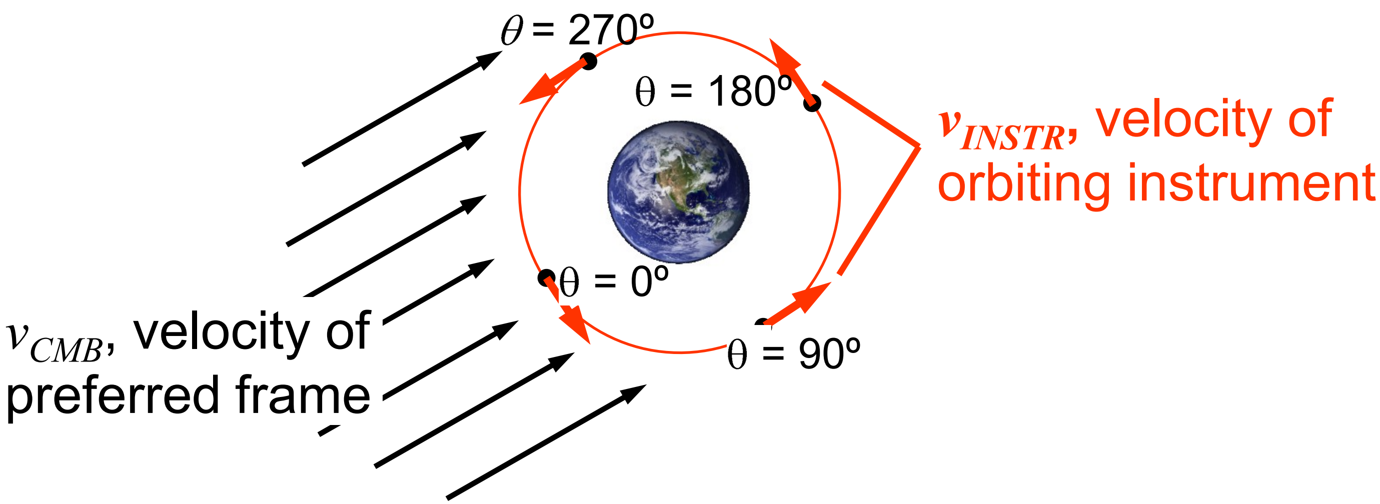
- **Disturbance reduction**
  - Microgravity
  - Seismic quietness
  - Relaxed stress due to self weight
  - Far away from time dependent gravity gradient noises

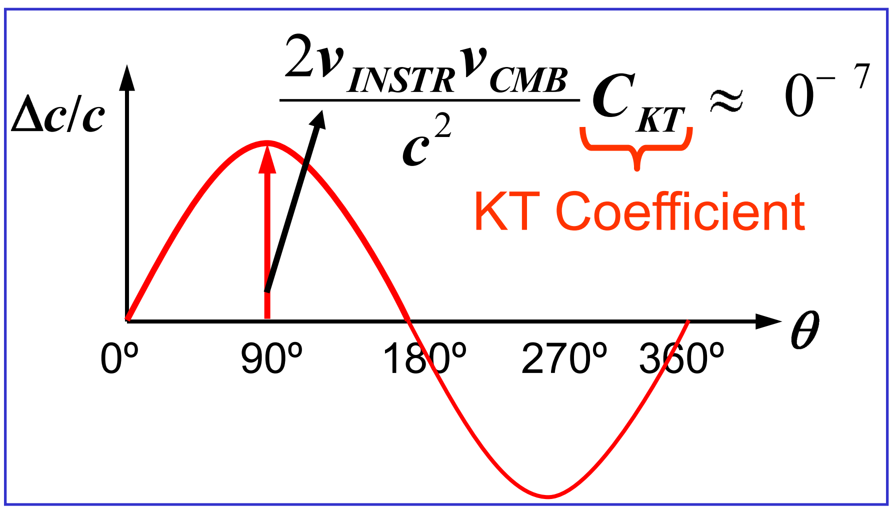
KT Improvement in Space:

- **Faster signal modulation** **×4 (√16)**
- **Higher velocity modulation** **×20 to ×30**
- **Other considerations** **~ 1 to 3**

Net Overall Advantage ≥ 100

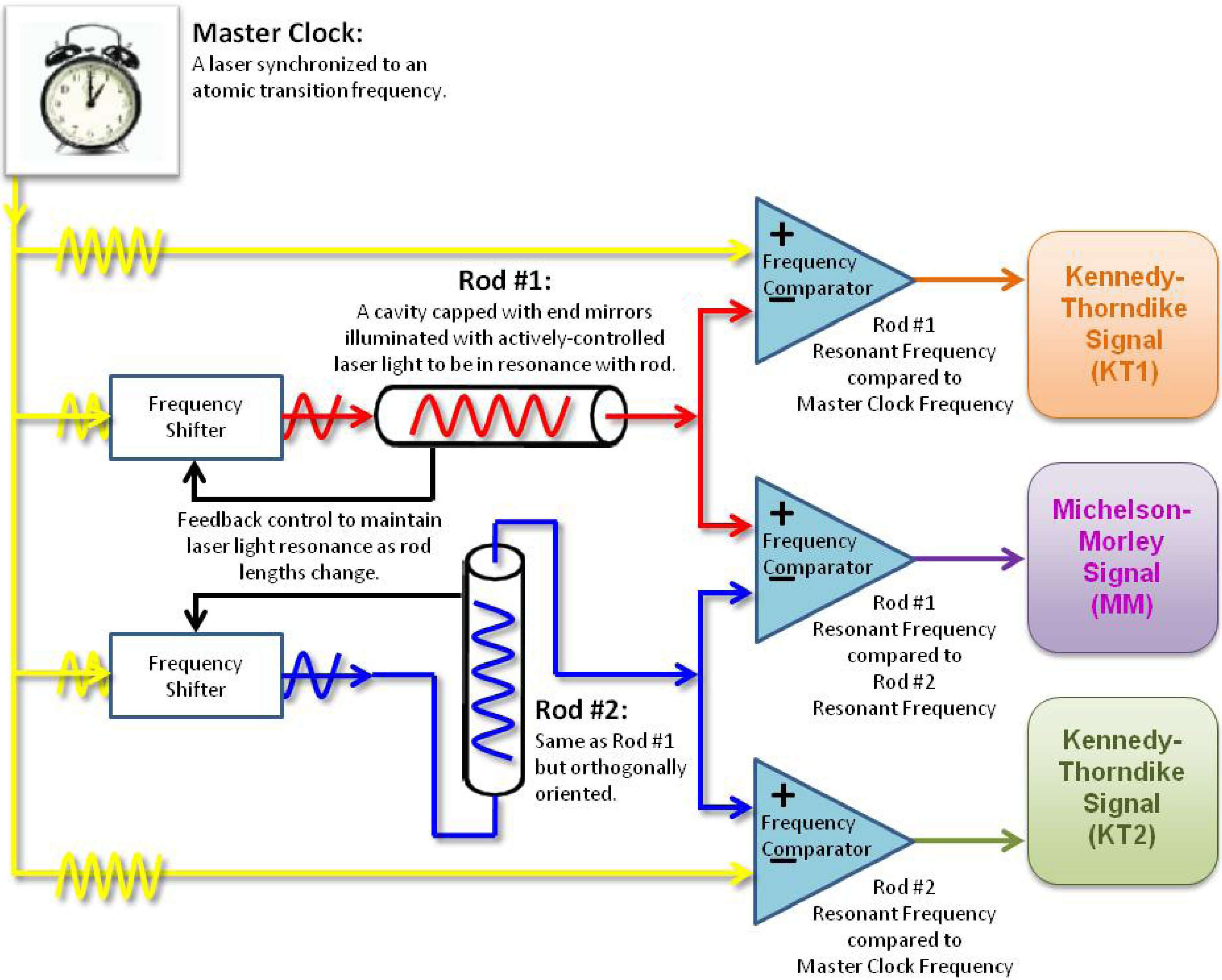
Measuring KT



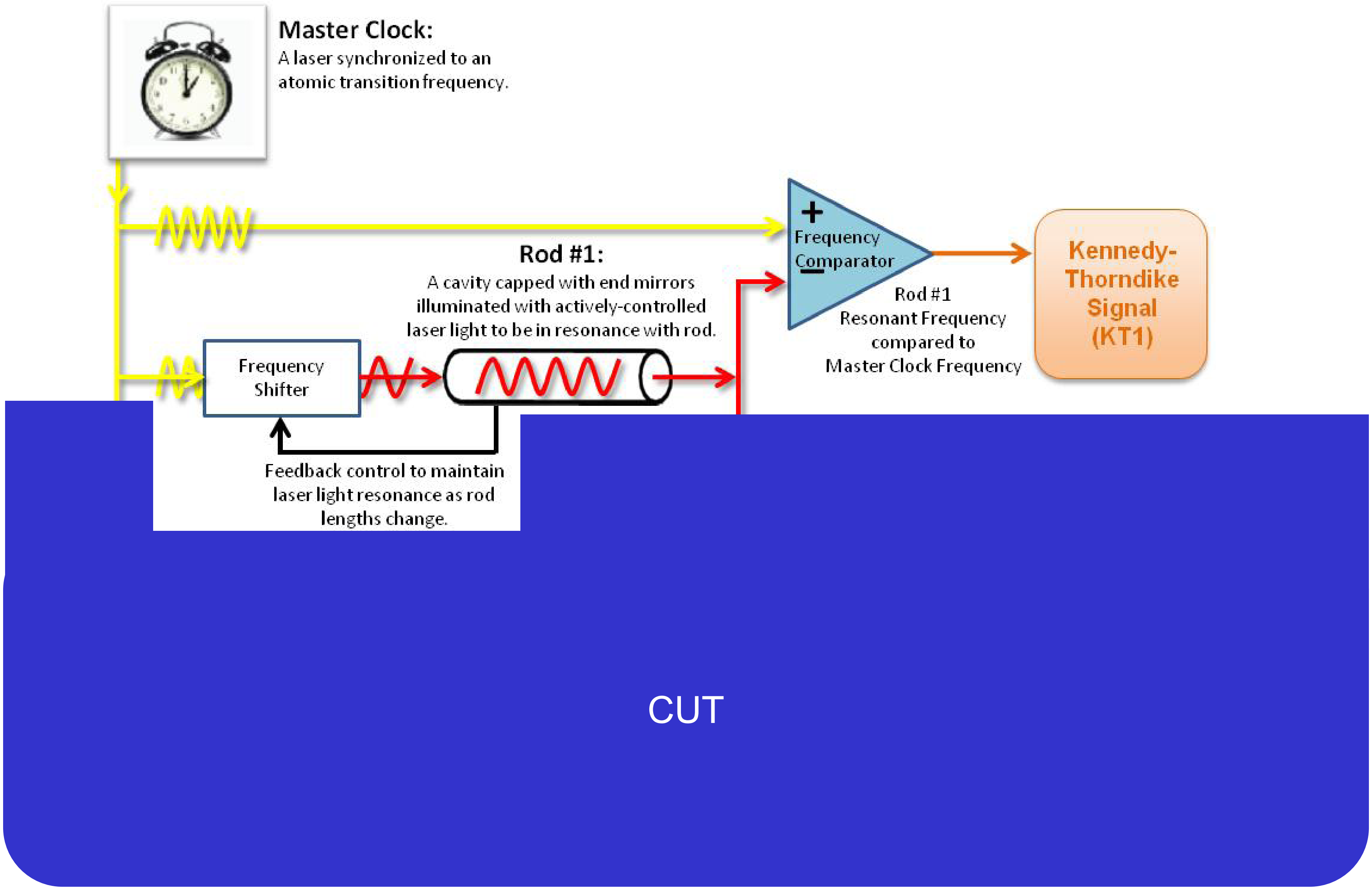


A velocity-dependent LIV would cause a Δ*c*/*c* variation at the orbital rate

STAR conceptual diagram



miniSTAR conceptual diagram



mSTAR Concept

Lipa, et. al. "Prospects for an advanced Kennedy-Thorndike experiment in low Earth orbit" arXiv:1203.3914v1[gr-qc]

Science

1) Lorentz Invariance Violations

2) Velocity boost c dependence
"Kennedy-Thorndike Experiment"

3) >100x state of the art

Science & Technology on Small Satellites

Education driven

International collaborations

Education

1) Graduate & Undergraduate

2) 3-5 year projects

3) Student led tasks

Technology

1) "Capable" small satellite bus
100 kg, 120 W, secondary payload

2) Advanced frequency standards

3) Precision thermal control

mSTAR Collaboration

- **Kingdom of Saudi Arabia**
  - *King Abdulaziz City for Science and Technology (KACST)*
  - *KACST – Stanford JCOE*
- **Germany**
  - *German Aerospace Center (DLR)*
  - *Bremen University*
  - *ZARM*
  - *Humboldt University, Berlin*
- **United States**
  - *NASA Ames Research Center (ARC)*
  - *KACST – Stanford JCOE*
  - *Stanford University*

Collaborating Institutions

Main Contributions

ALL

Science and EP&O

KACST

Spacecraft, Launch,
Mission Operations

DLR & Bremen

Iodine Clock,
Instrument Integration
Mission Operations

JCOE

*Optical cavity **to TRL 4***

Ames Research Center

*Optical cavity **to TRL 6***
Mission Operations

mSTAR Technology Challenges

Advanced frequency standards

Optical cavities

Molecular clocks

$$\delta\,/\,f \leq 0^{-\ 5}/\sqrt{\mathrm{Hz}}$$

nano Kelvin thermal control

Thermal shields

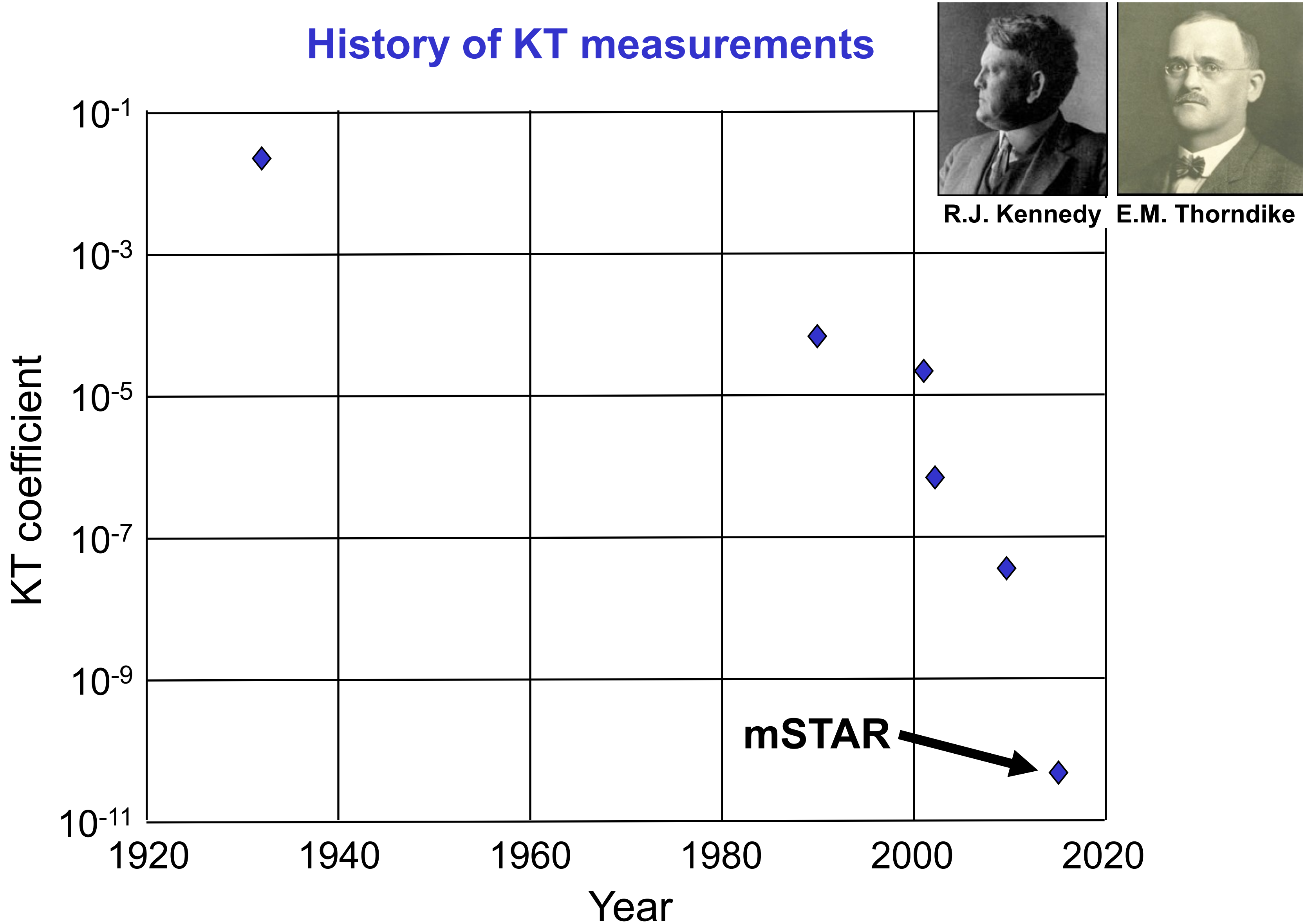
Control algorithms

Optical thermometry

$$\delta\ (\mathit{Inner\ shield})/\Delta\ (\mathit{Outer\ shield}) \leq 0^{-}$$

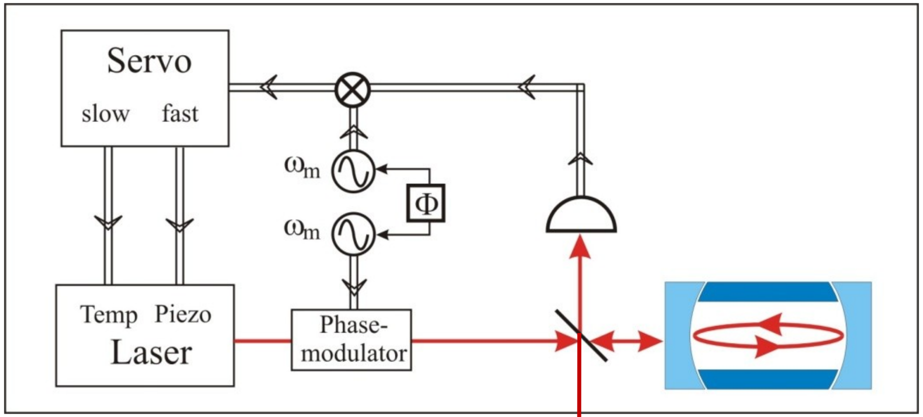
$$\delta\ (\mathit{Inner\ shield})/\Delta\ (\mathit{Outer\ shield}) \leq 0^{-\ 2}$$

KT Coefficient

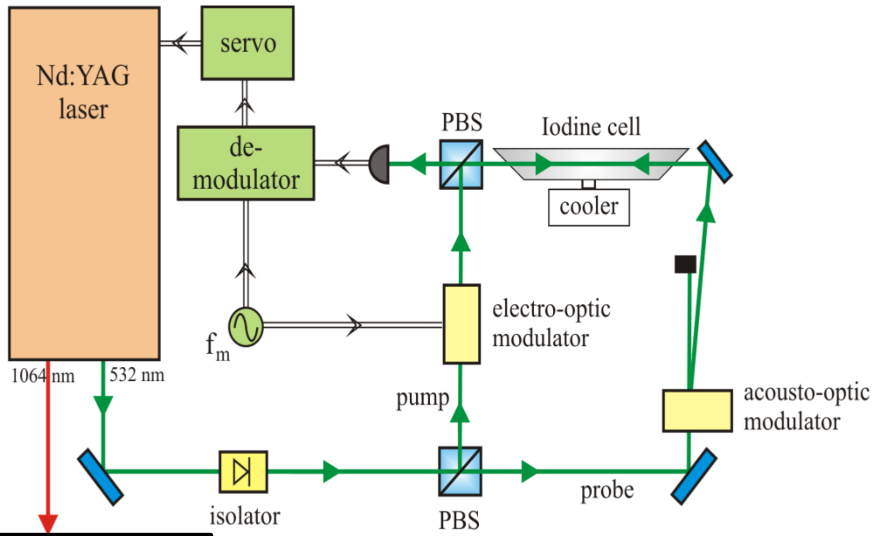


Modern Kennedy-Thorndike Tests

clock based on length standard



clock based on atomic transition

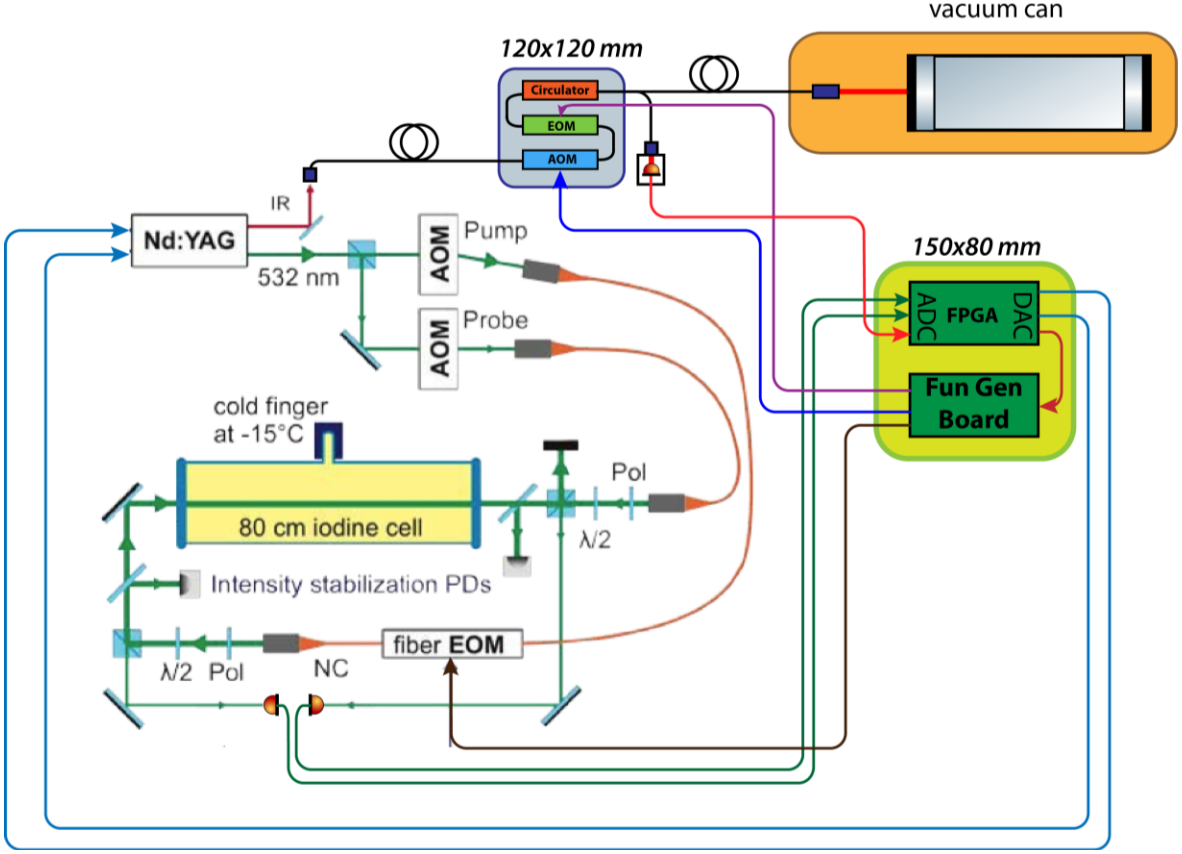


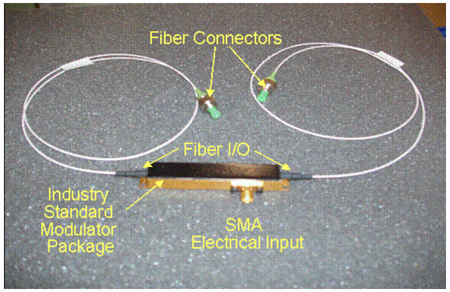
beat measurement

with

varying laboratory velocity

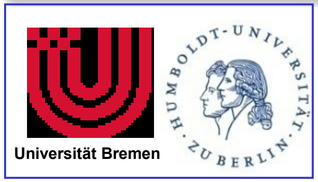
miniSTAR optical diagram

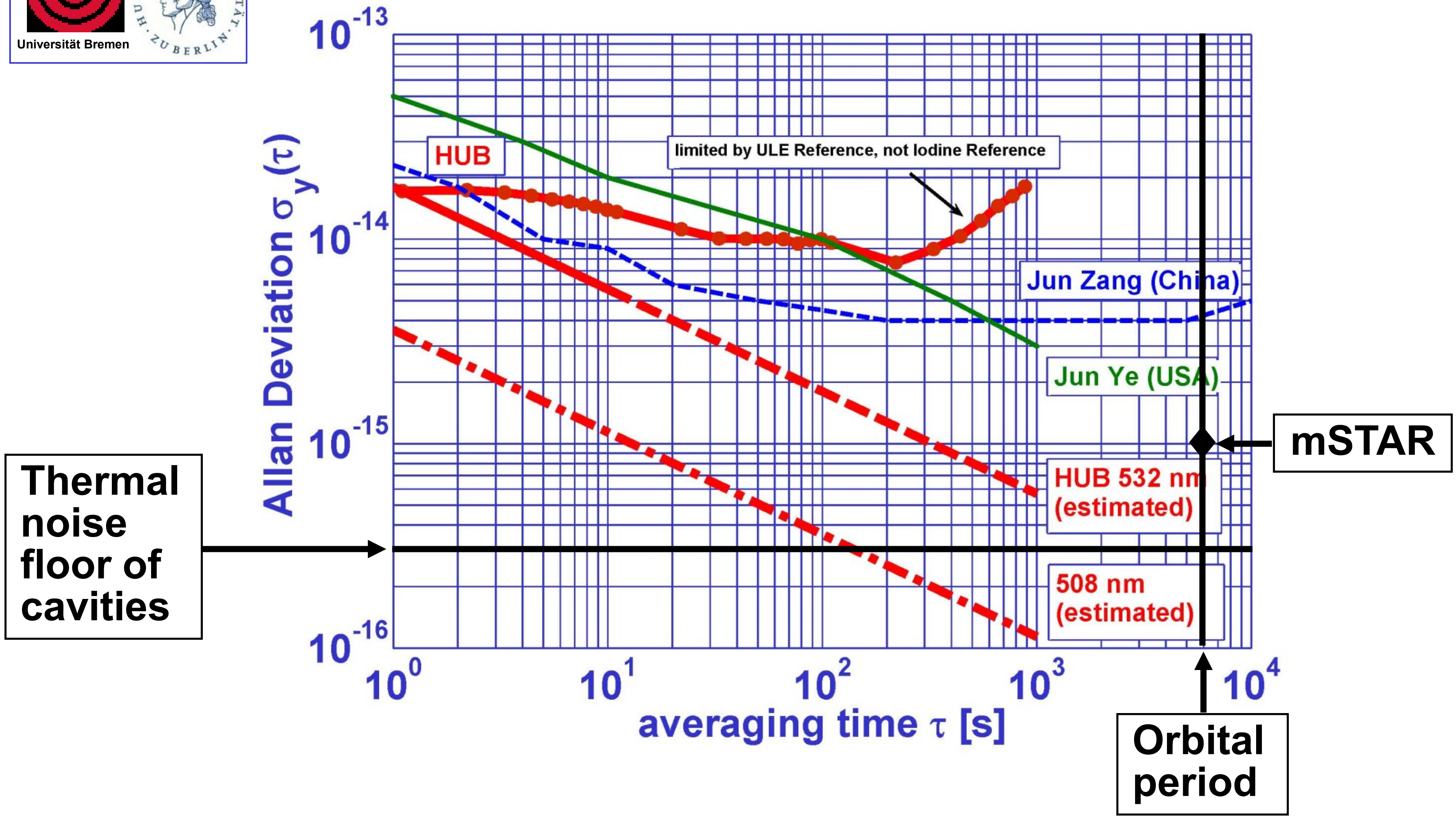




- RF modulation obtained by frequency generation board
- RF demodulation executed digitally by FPGA board (with RF ADC channels)
- Digital VCO by onboard FPGA
- Laser PZT and Temp controlled by FPGA
- Science signal contained in the digital VCO error signal

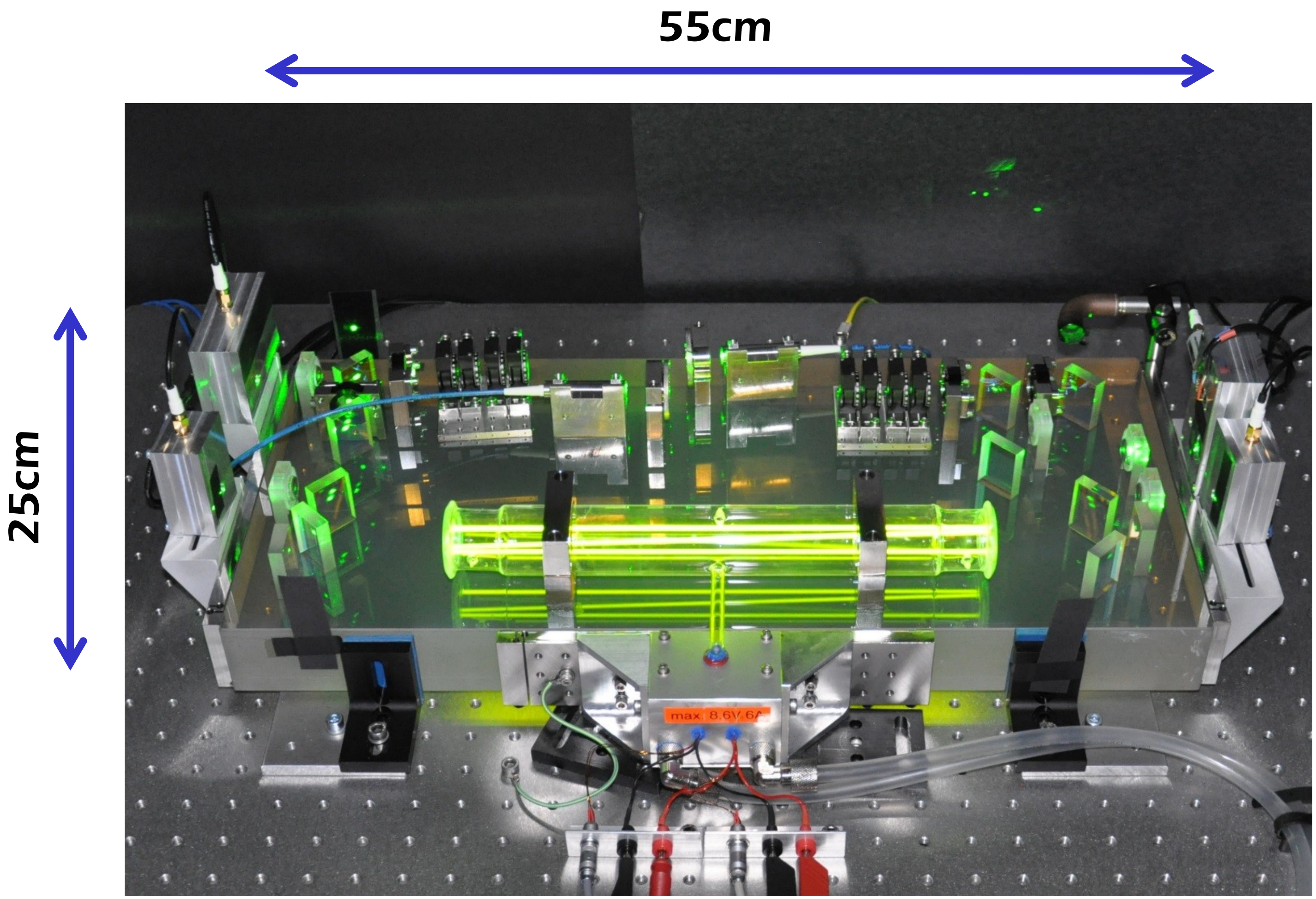
State of the art: Iodine vs. cavity





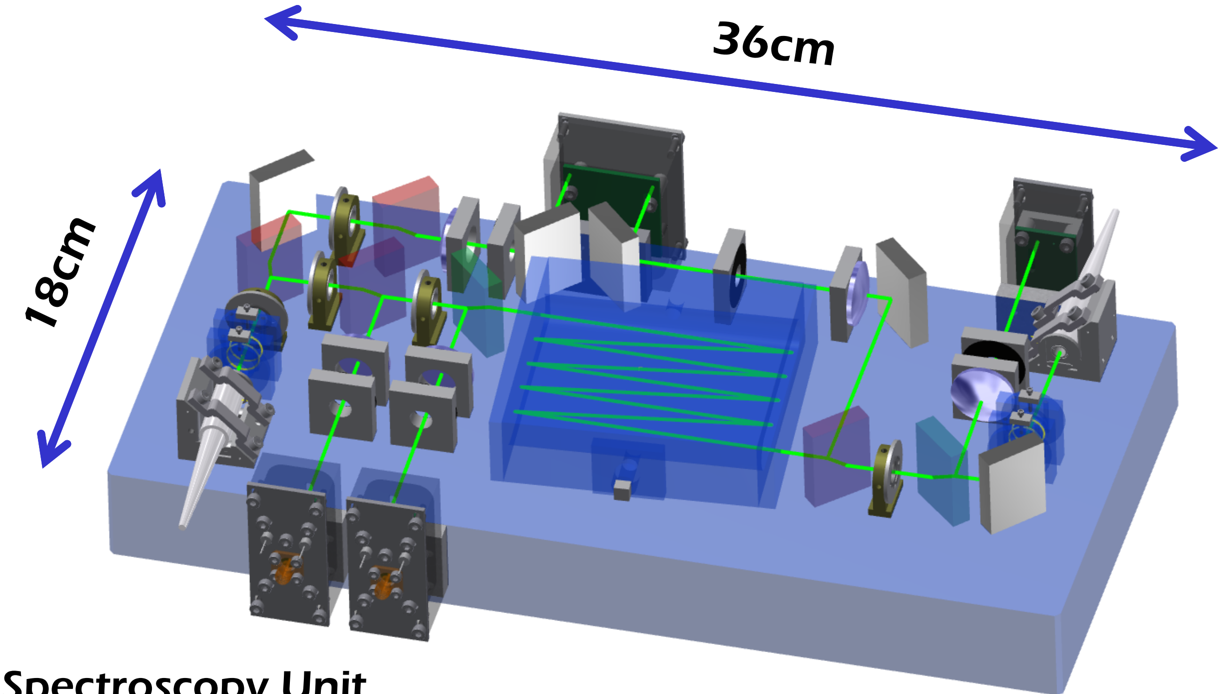
Iodine Frequency Reference EBB Level

Universität Bremen



Spectroscopy Unit,
Braxmaier et al, 2013

Iodine Frequency Reference EM Level



Spectroscopy Unit,
Braxmaier et al, 2013

Next steps:

- EBB to EM level
- Space qualification

Optical cavity

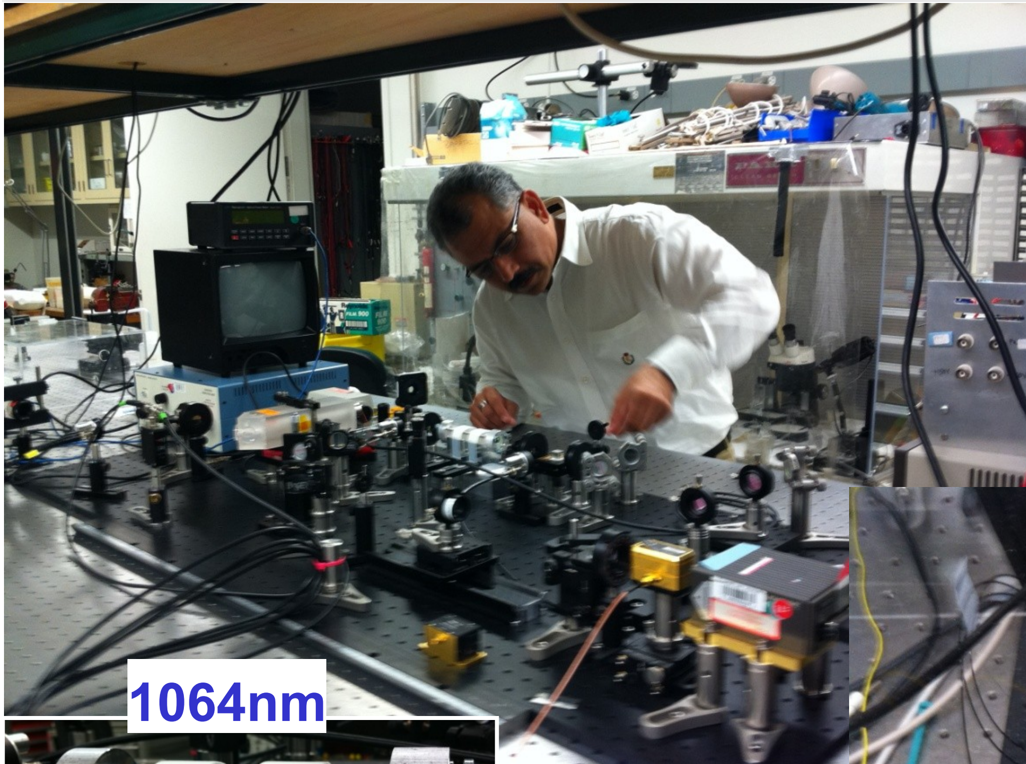
Key optical cavity parameters:

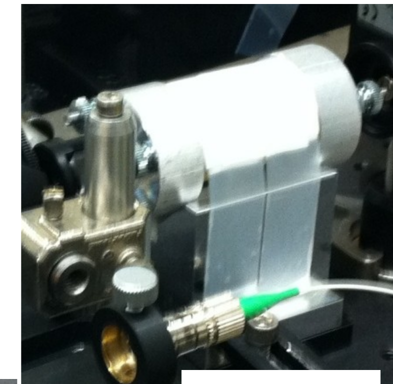
- $\delta L/L < 10^{-17}$ at orbit and harmonics with 2 years of data
- $\delta L/L < 10^{-17}$ at twice spin period with 2 years of data

Derived requirements:

- Expansion coefficient: $< 10^{-9}$ per K
- Operating temperature: within 1 mK of expansion null (~ 15°C nom)
- External strain attenuation: $> 10^{12}$
- Stiffness: $\delta L/L < 10^{-9}$ per g, 3-axis
- Implied material: ULE glass

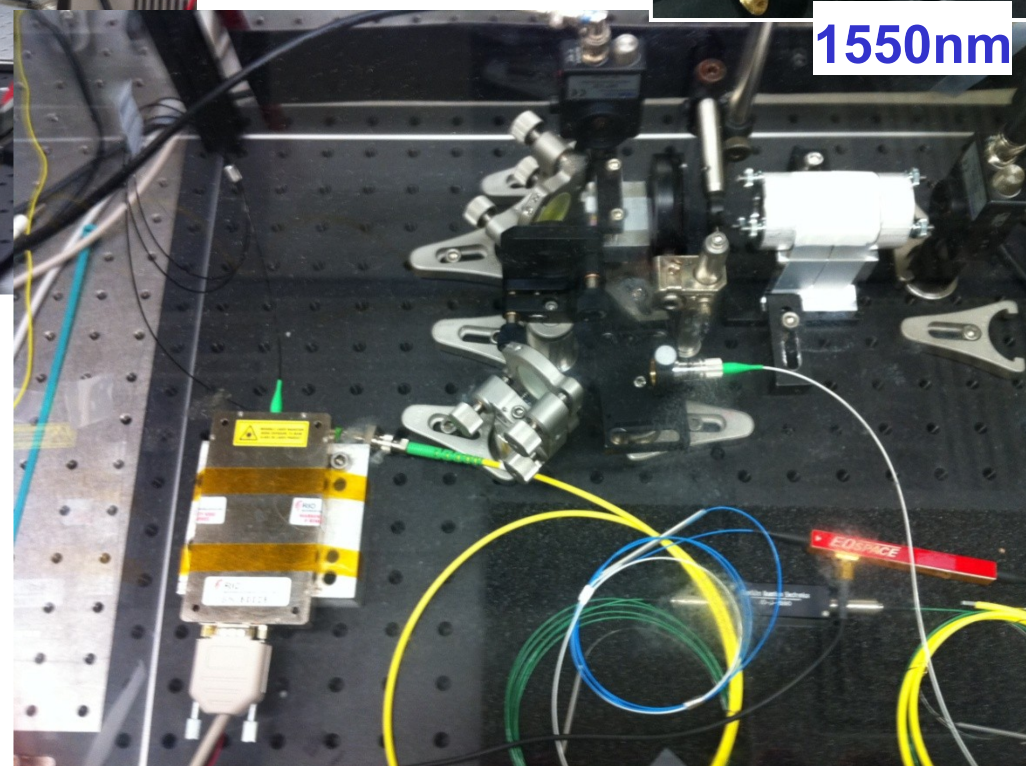
Optical cavity work at Stanford





1064nm

1550nm



Thermal enclosure

Main Requirements:

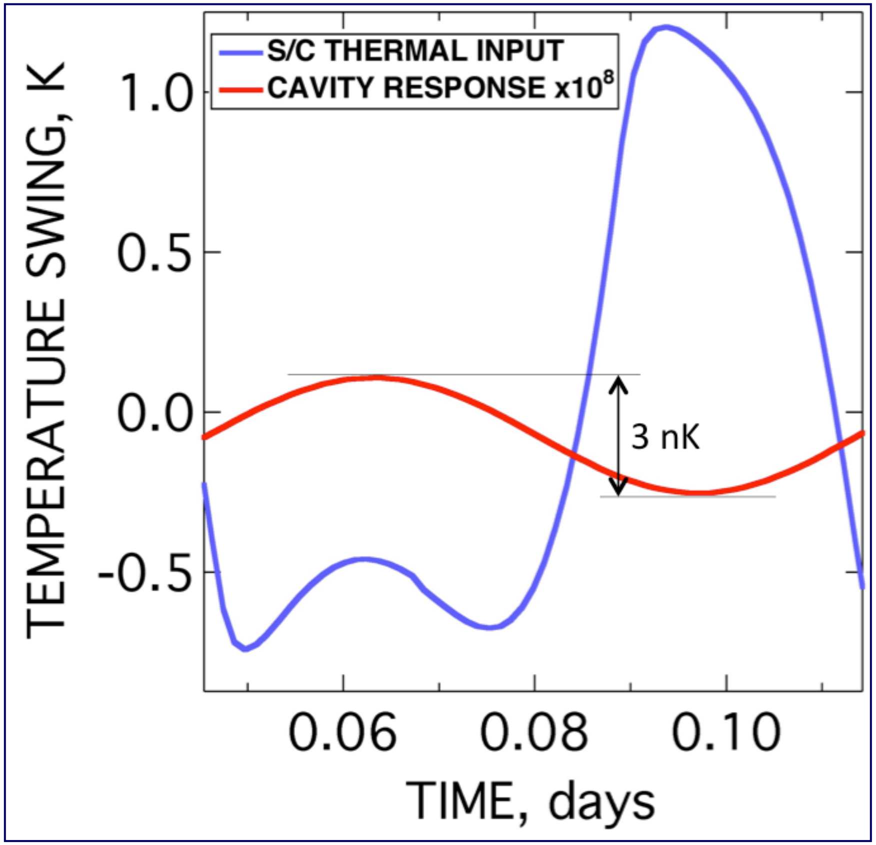
- Thermal stability
- Stress attenuation
- Launch and space compatible

Thermal performance:

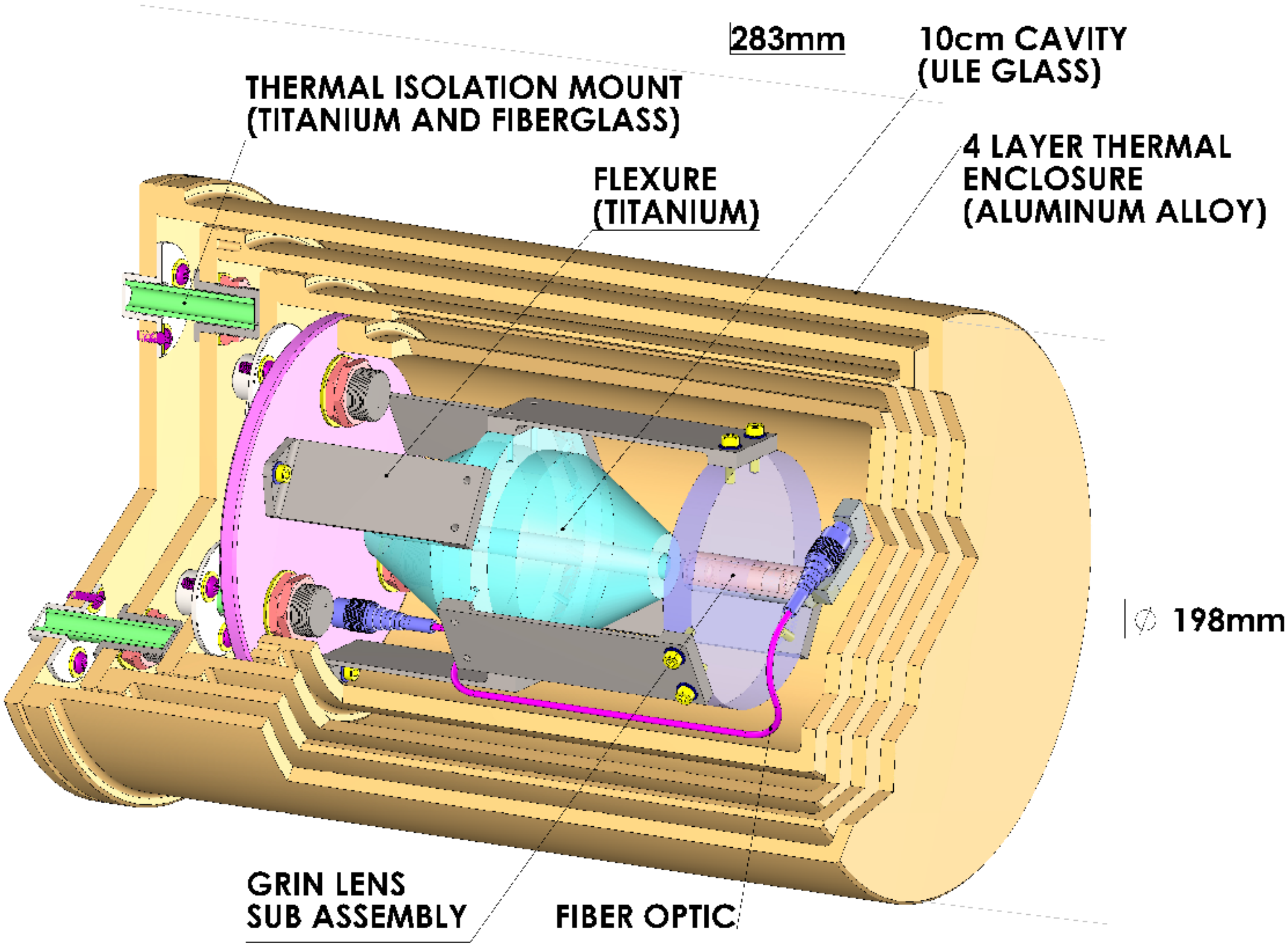
- Cavity $\delta L/L < 10^{-17}$ (2 yr data) at:
  - orbital period and harmonics
  - twice spin period

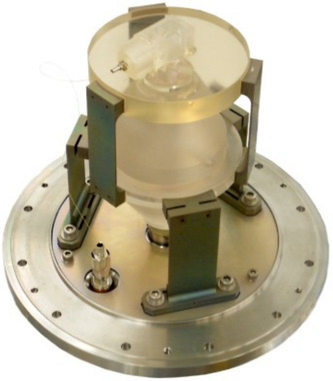
Derived requirements <2 yr>:

- Stability of 10^{-8} K at orbit
- Gradient ~ 10^{-9} K/cm at orbit
- Maintain temperature to 1 mK



Thermal enclosure & cavity

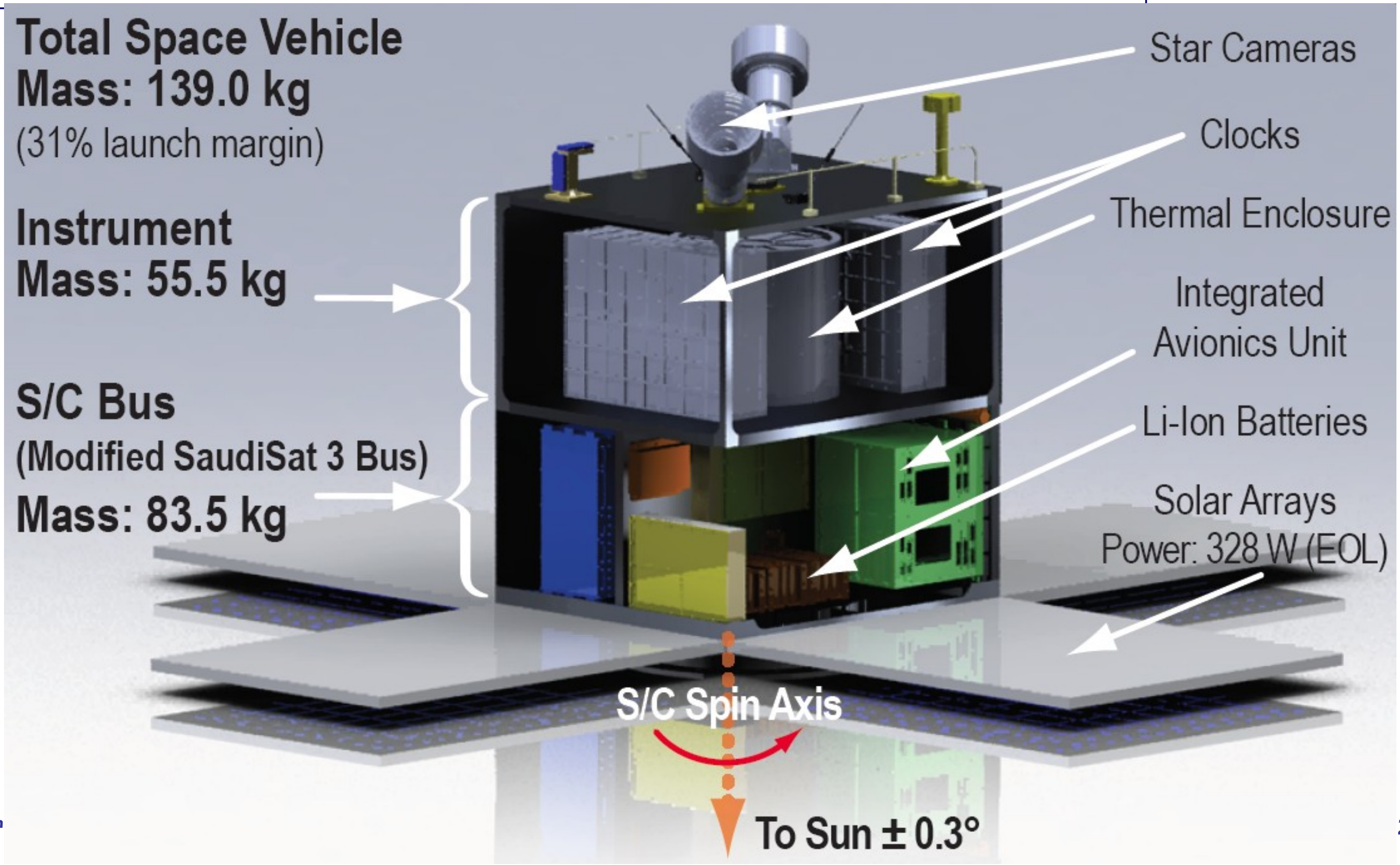




(GRACE-FO)

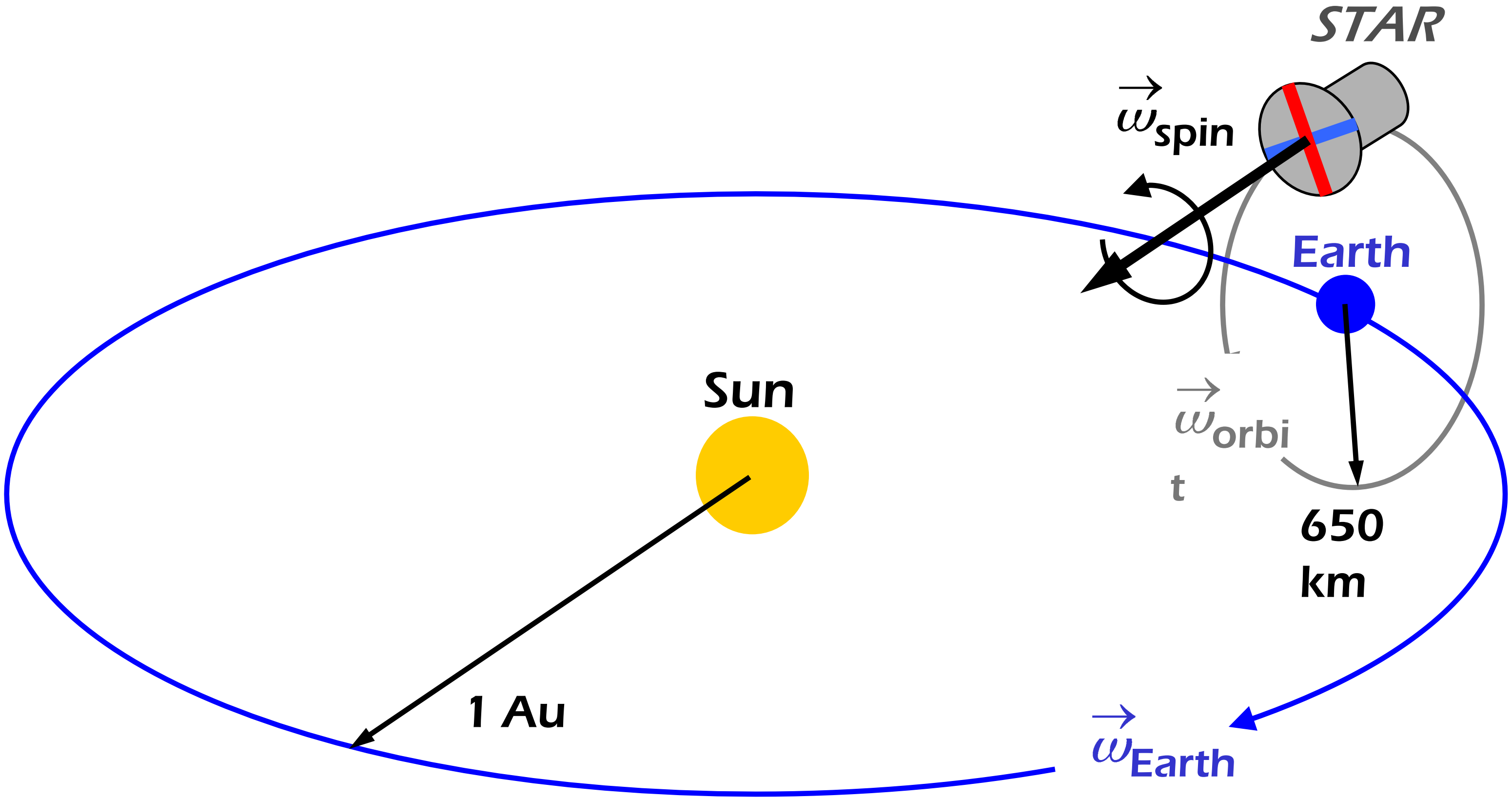
mSTAR mission characteristics

- Secondary payload: **Saudi Sat 4 (UV-LED Sat - April 2014)**
- Circular sun-synchronous ~ 650 km orbit
- Launch 2017
- 2-year mission lifetime



STAR Geometry and Frequencies:

•	Spacecraft spin rate (nominal):	$\Rightarrow \omega_{spin}$ = 1/(100 sec)	= 10 mHz
•	Orbit: 600 km Sun-sync (nominal):	$\Rightarrow \omega_{orbit}$ = 1/(98 min)	= 0.17 mHz
•	Earth's orbital rate:	$\Rightarrow \omega_{Earth}$ = 1/(1 yr)	= 32 nHz



mSTAR Status

- **2008 Concept proposed as a NASA MOO SMEX**
- **2011 Second proposal submitted as NASA MOO**
- ***Reviews pointed out some weaknesses***
  - TRL levels, Complexity, Cost
- **Current efforts:**
  - **Bring instrument to TRL ≥ 5**
    - Using internal resources
    - Contributions from partners
    - Reduce instrument complexity

mSTAR Schedule

mSTAR Milestone Draft				
Phase	Name	Activity	Completion	Months
1	Nice Workshop	Draft Proposal	Oct-2013	1
2	Requirements Review	Design study	Apr-2014	6
3	PDR	HW & SW development	Jan-2015	9
4	CDR	HW & SW to TRL 4	Jan-2016	12
5	Integration Review	HW & SW to TRL 6	Jan-2017	12
6	Launch Review	Integrated System	Jul-2017	6
7	Launch	Launch activities	Dec-2017	6
8	Science Mission	Mission Operations	Dec-2019	24
9	Science Results	Data Analysis	Dec-2020	12

Questions?

Kostelecky, Scientific American, 2002

Thank You